MSE 214 Composites B

Les matériaux composites

- Les fibres, les matrices
- Micromécanique et anisotropie
- Les procédés de mise en oeuvre
- Les développements récents

  Biocomposites

  Composites fonctionnels
  Nanocomposites

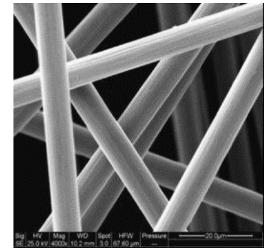
  …

Références:

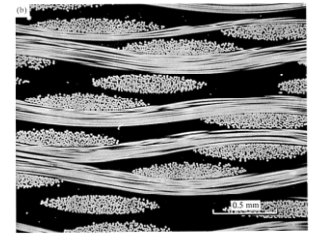
Traité des Matériaux, vol. 15
" Matériaux composites à matrice organique"

Presse Polytechniques et Universitaires Romandes

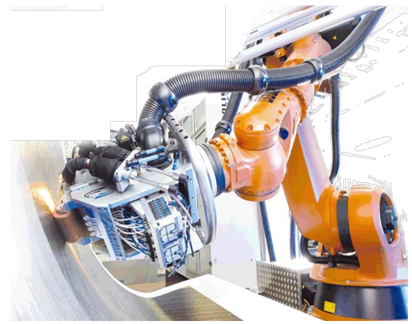
pierre-etienne.bourban@epfl.ch



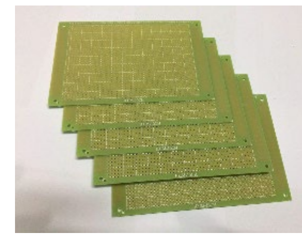
www.reinforcedplastics.com



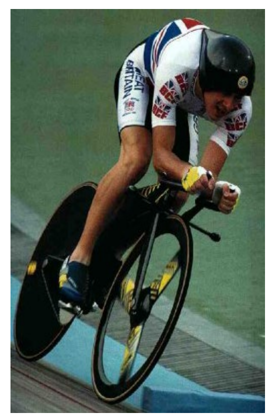
Des fibres aux stratifiés



www.coriolis-composites.com



Hublot



Rigidités et anisotropies exploitées

BMW i8 automobile.challenges

Mise en œuvre des composites

- Introduction
- Transformation des thermodurcissables (TD)
- Techniques de fabrication des TD
- Transformation des thermoplastiques(TP)
- Techniques de fabrication des TP
- Comparaison et sélection des techniques

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Introduction

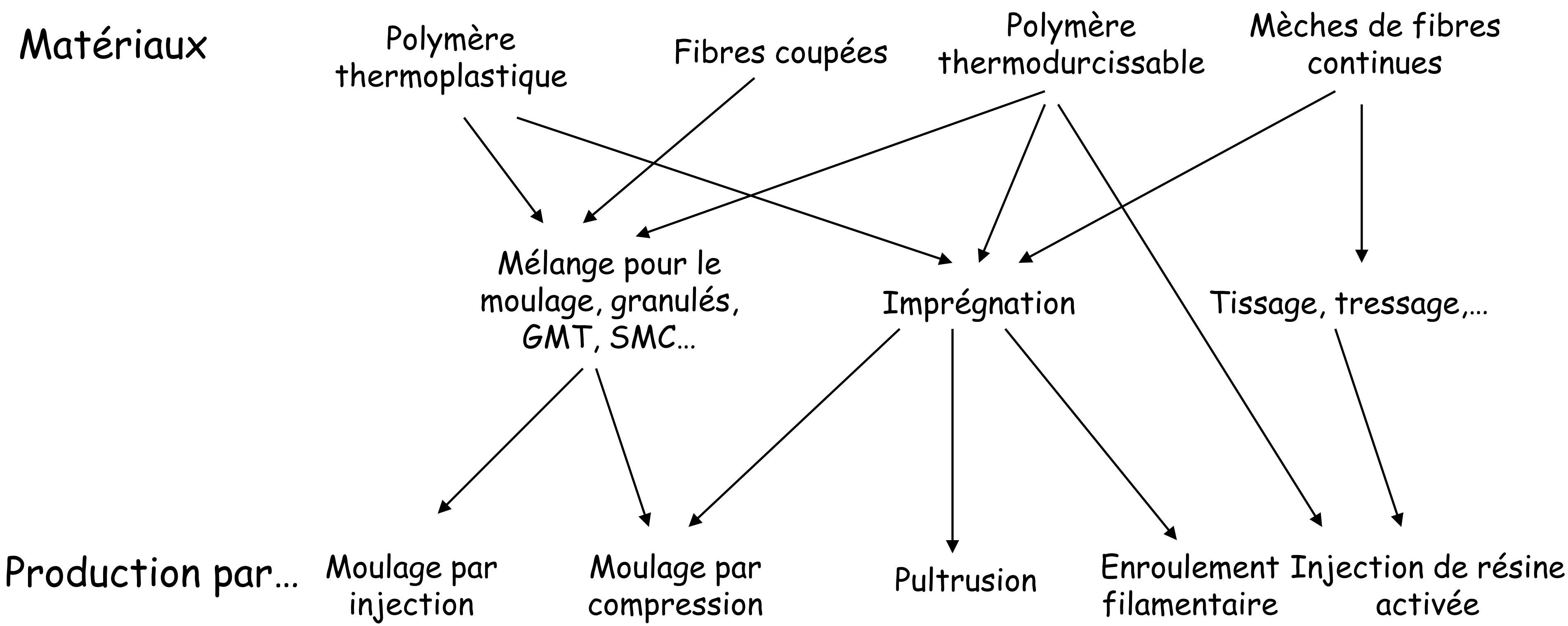
Mise en œuvre des composites ← Type de matrice

Mise en œuvre des composites ← Imprégnation des renforts

Mise en œuvre des composites ← Types de semi-produits

Mise en œuvre des composites ← Consolidation

Des matériaux aux produits



Mise en œuvre des composites

(a) Préimprégnés → moule → mise en forme

(b) Fibres → renfort textile → moule

Résine → moule

moule → imprégnation par moulage

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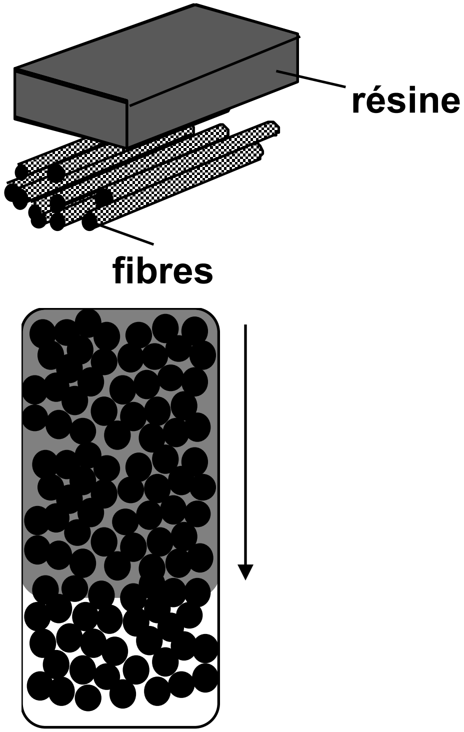
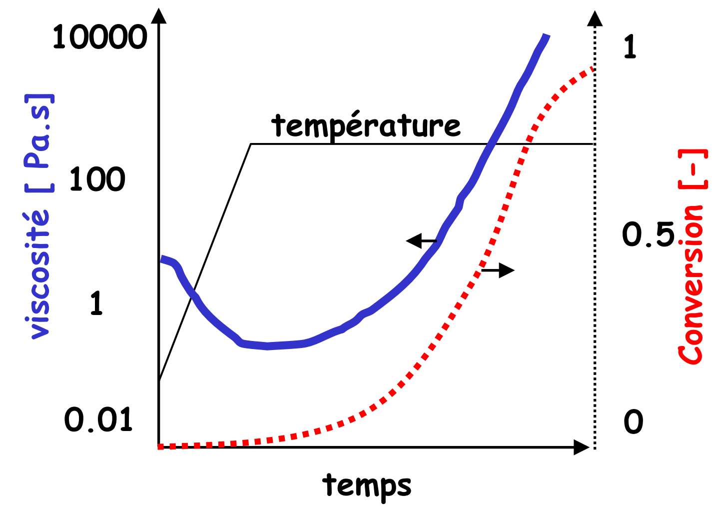
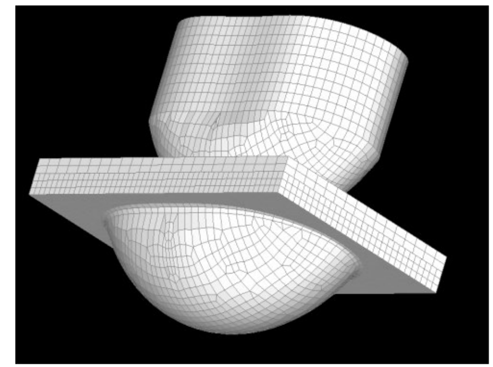
Les phénomènes







Tranfert de chaleur, écoulement, formage….

Imprégnation

Transformation de la matrice

- Polymérisation, réticulation des termodurcis
- Fusion et consolidation des thermoplastiques

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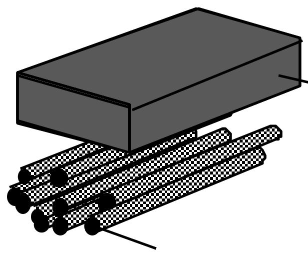
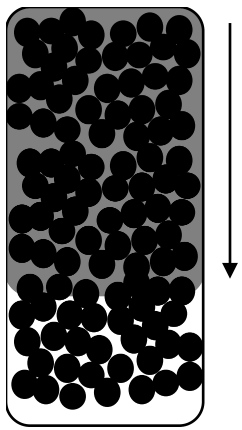
Imprégnation

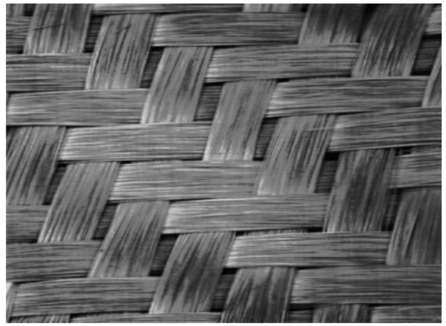


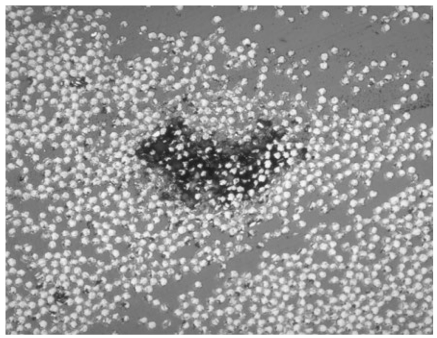
$$t_{\text{imprégnation}} = \eta \frac{(1 - V_f)L^2}{2K(P_a - \Delta P_c)}$$

Loi de Darcy



Temps d'imprégnation
Volume à imprégner 1-Vf
Viscosité de la résine η
Distance à imprégner L
Perméabilité du renfort K
Pression appliquée P_a
Pression capillaire P_c
Contre-pression du lit de renfort





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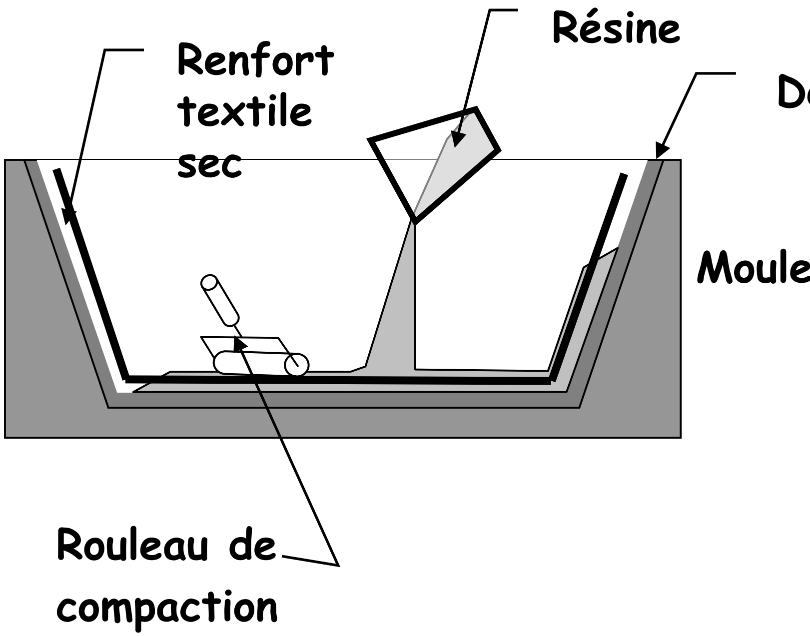
Moulage au contact



Fabrication de bateaux
Structures d'avions
Structure du génie civil

Avantages :	**Inconvénients :**
Facilité de mise en oeuvre	Faibles cadences de production
Investissements très faibles	Main d'oeuvre importante
Sans limitation de dimensions	Epaisseur difficile à contrôler
Main d'oeuvre peu qualifiée	Une face brute

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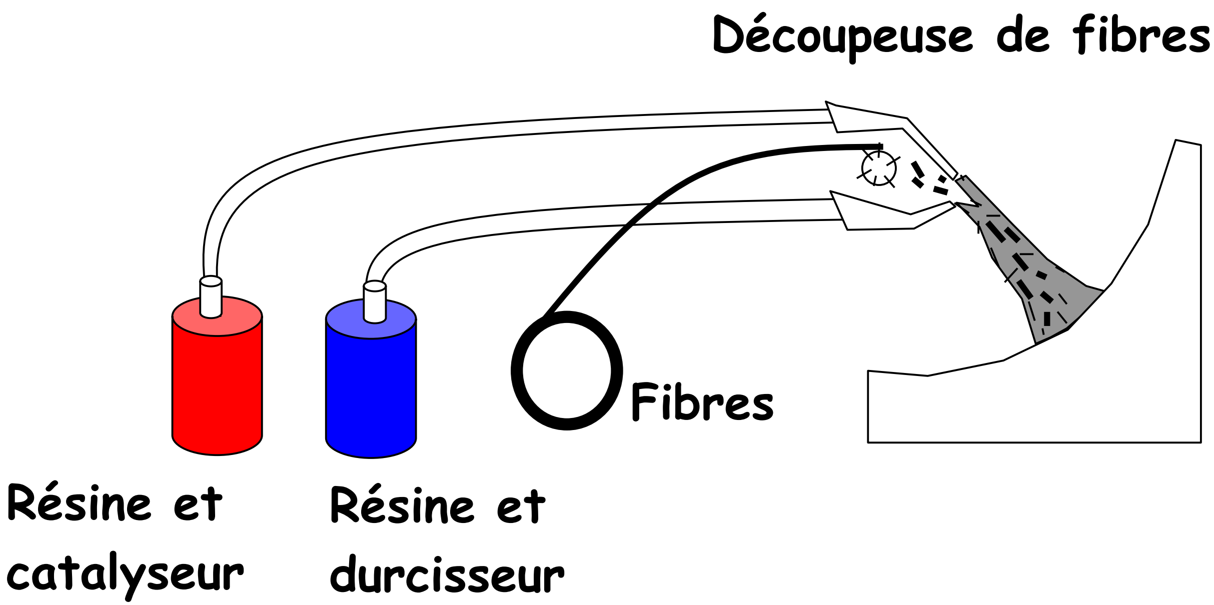
Moulage au spray

Avantages :	Inconvénients :
Cadence plus rapide que le moulage au contact Sans limitation de dimensions Equipements pas trop importants	Main d'oeuvre importante et qualifiée Peu de constance dans l'épaisseur Propriétés mécaniques pas très élevées



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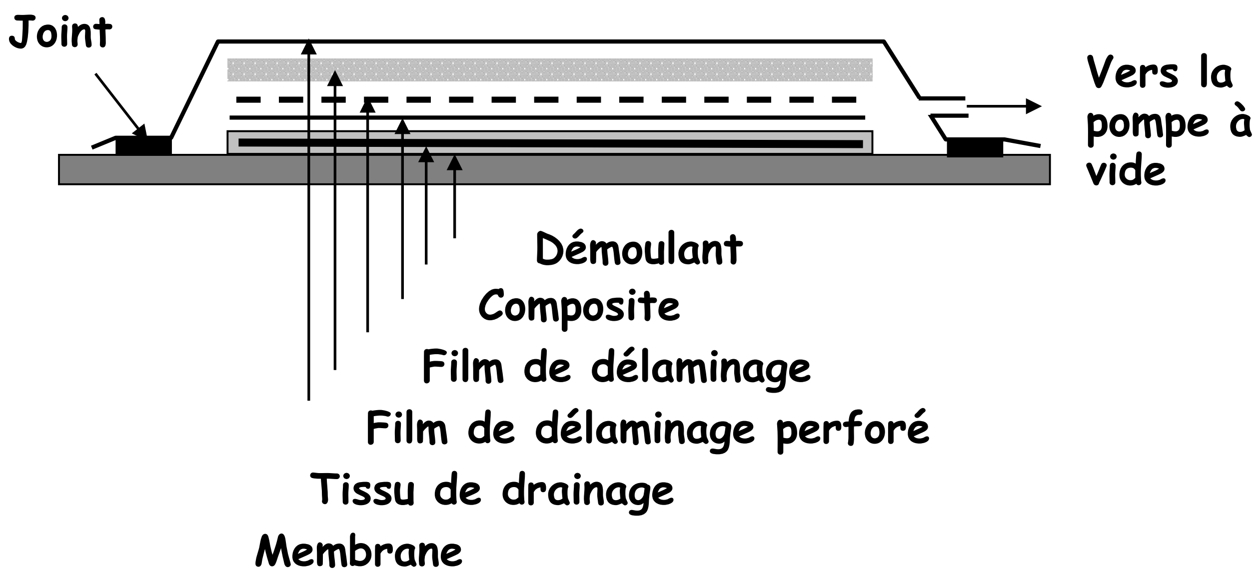
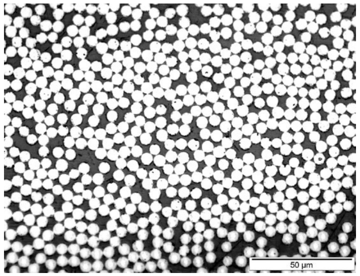
Moulage sous vide

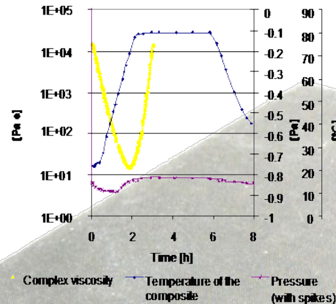


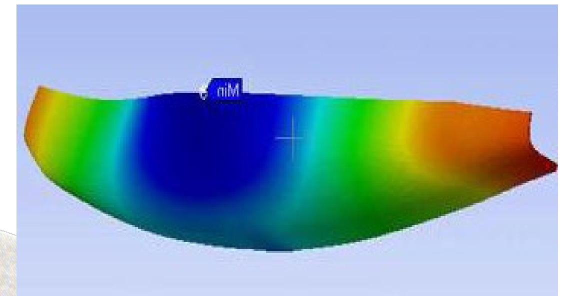
Avantages :	Inconvénients :
Facilité de mise en oeuvre Investissements faibles	Faibles cadences de production Main d'oeuvre importante

De la fibre à la coque



process





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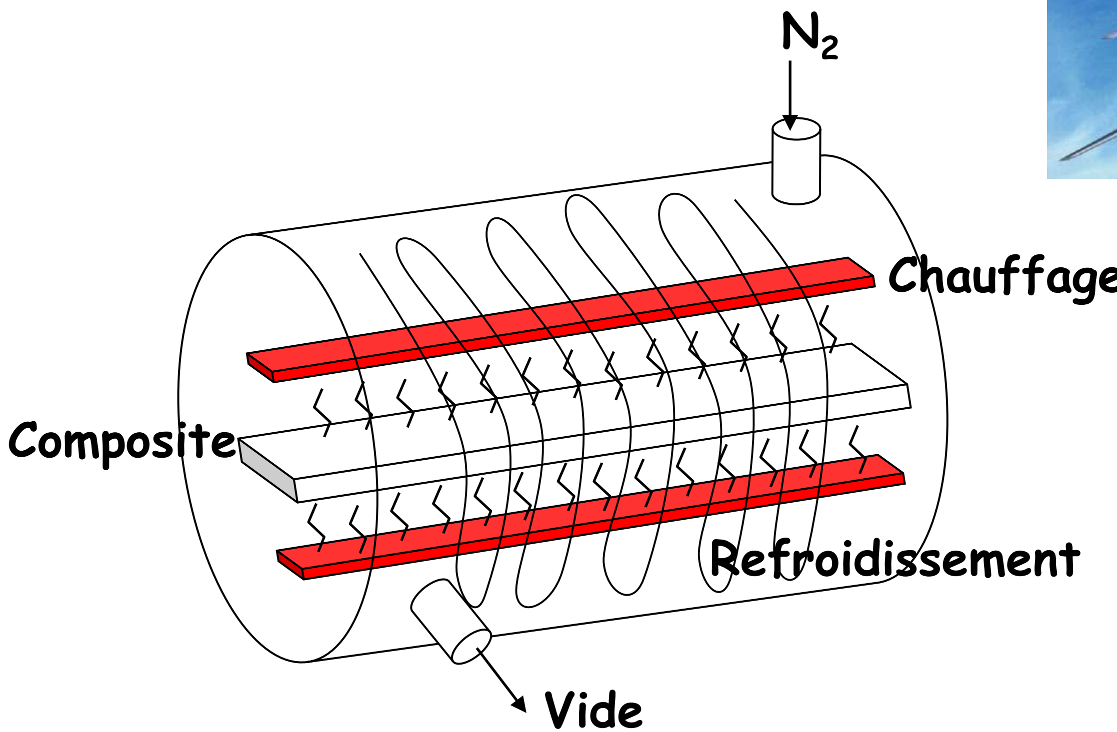
Moulage à l'autoclave



Avantages :	Inconvénients :
Contrôle des paramètres Bonne qualité des composites	Investissements Faibles cadences de production

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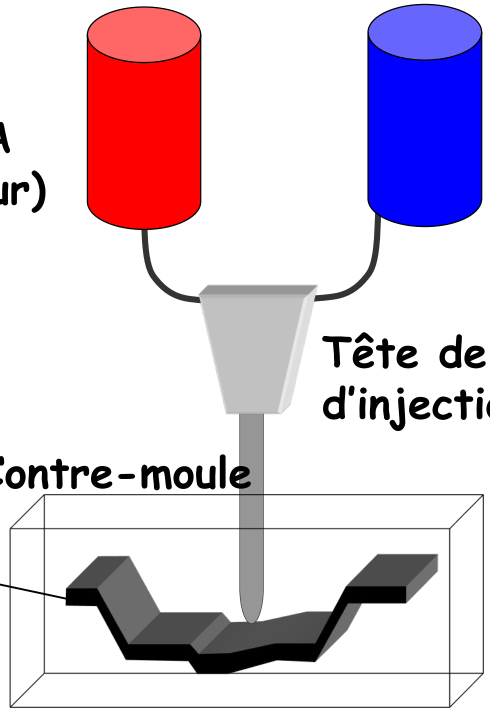
Transfert et injection de résine



Reaction injection moulding (RIM)
Resin transfer moulding (RTM)

TD et TP (Polyuréthane, PA)
Prépolymères réactifs
Version avec fibres courtes RRIM
ou fibres longues dans le moule SRIM
Réaction dans le moule, après imprégnation

Avantages :	Inconvénients :
Faible consommation d'énergie Pression de moulage faible Possibilité de fabrication de grandes pièces complexes Cycles de moulage courts	Performances thermiques limitées

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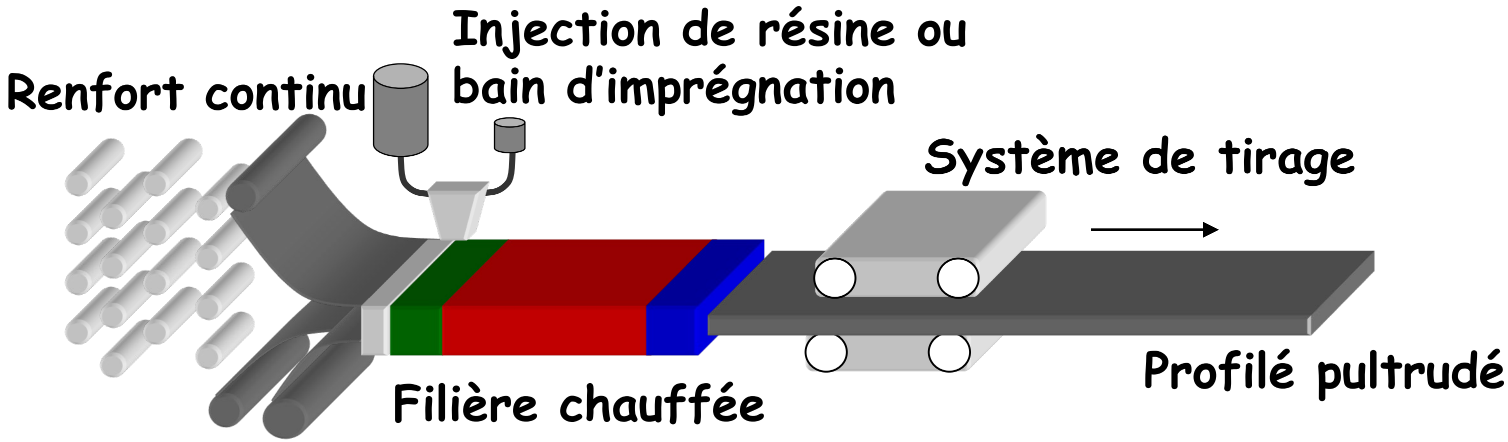
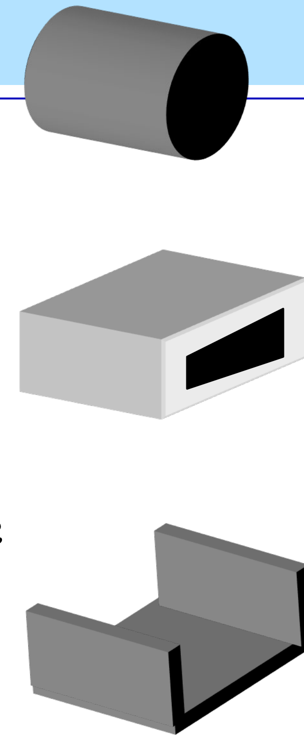
Pultrusion





Surtout thermodurcissables et thermoplastiques
Fibres sèches ou fibres préimprégnées

Avantages :	**Inconvénients :**
Méthode de production en continu Bon contrôle du pourcentage de renfort Grande automatisation possible Vitesses de production élevées Réalisation de formes variables	Investissements assez importants Limitations dans les variations d'épaisseur.

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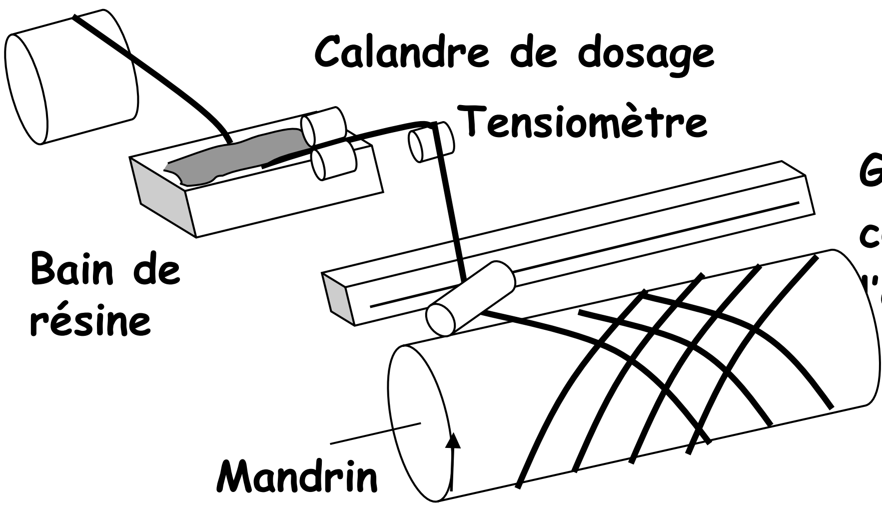
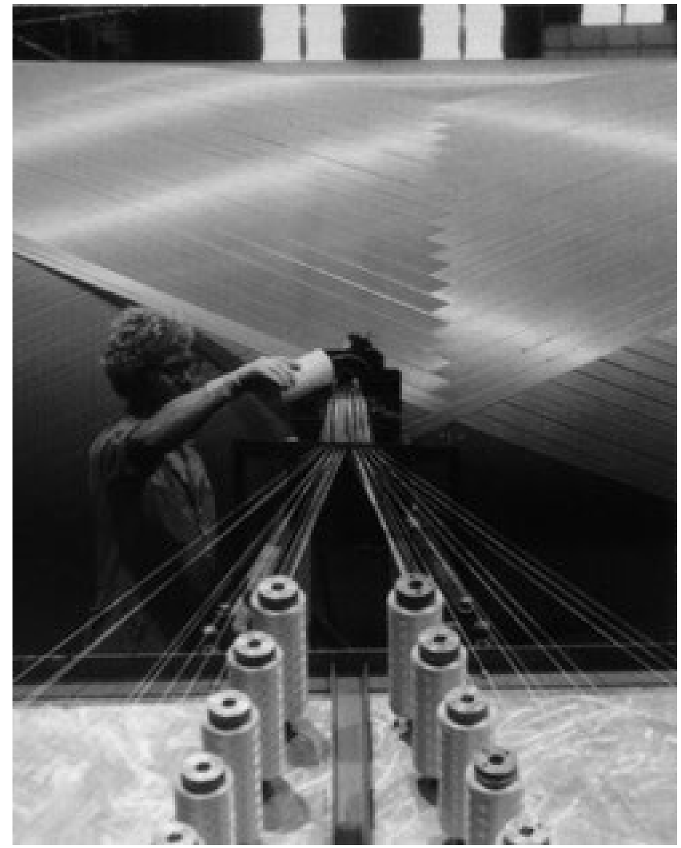
Enroulement filamentaire

Réservoirs, réservoirs sous pression, tubes….





Avantages :	Inconvénients :
Moulage de pièces de révolution, sans limitation de dimensions Face intérieure lisse Taux de fibres jusqu'à 80% Orientation des fibres dans le sens préférentiel	Investissements importants Cadence de fabrication faibles Face extérieure brute

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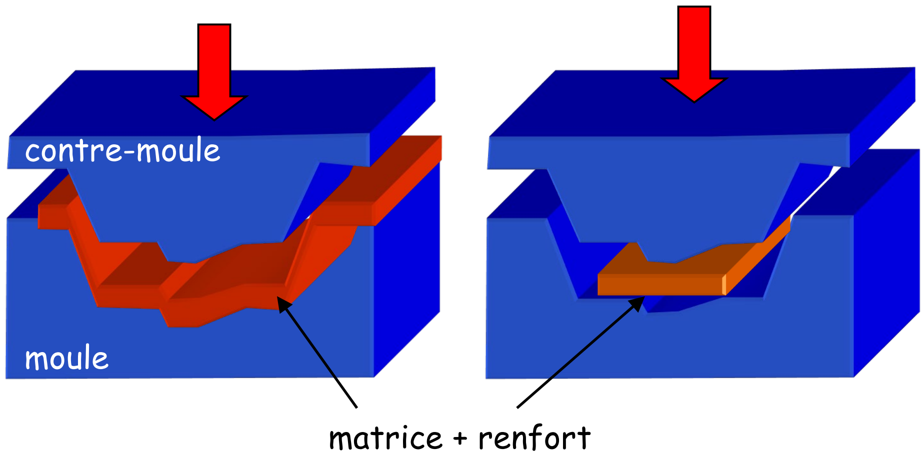
Moulage par compression



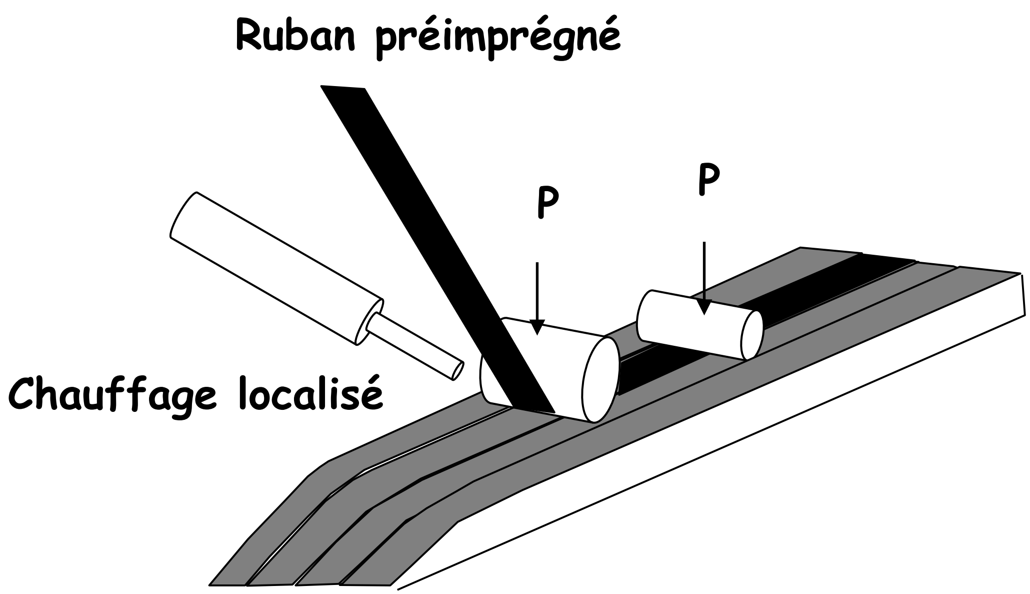
Sans écoulement **Avec écoulement de matière**

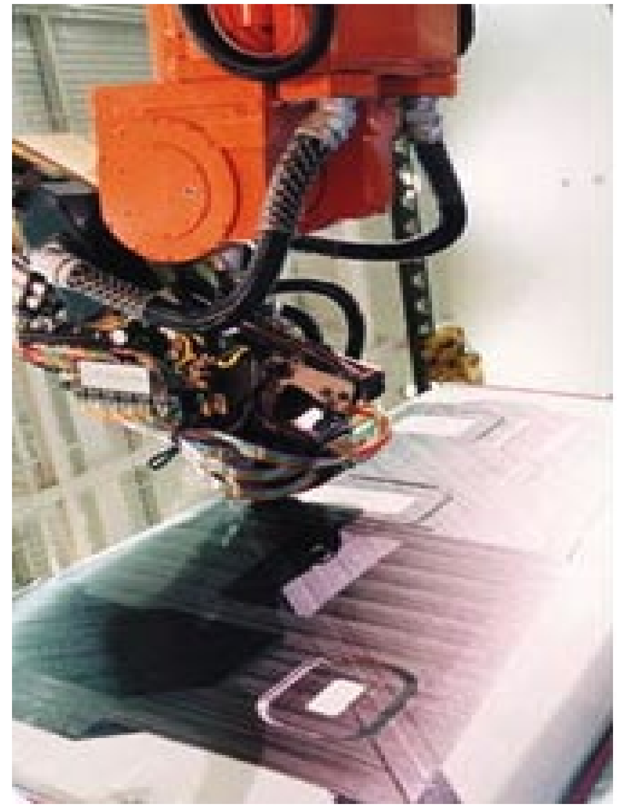
Thermodurcissables et surtout thermoplastiques
Semi-produits à fibres longues :
SMC: sheet moulding compound, verre+ polyester
GMT, TRE: glass mat thermoplastiques, verre + PP

Capots, carrosserie de voiture, camion, plaques semi-finies….

Avantages :	**Inconvénients :**
Moulages de pièces de grandes dimensions	Coût de l'outillage
Qualité des pièces	Bavures importantes
Cadences élevées	Dosage préalable nécessaire pour chaque empreinte

Dépose de ruban





Avantages :	Inconvénients :
Automatisation Placement préférentiel des renforts Pièces convexes et concaves	Investissements importants Contrôle du soudage entre les rubans

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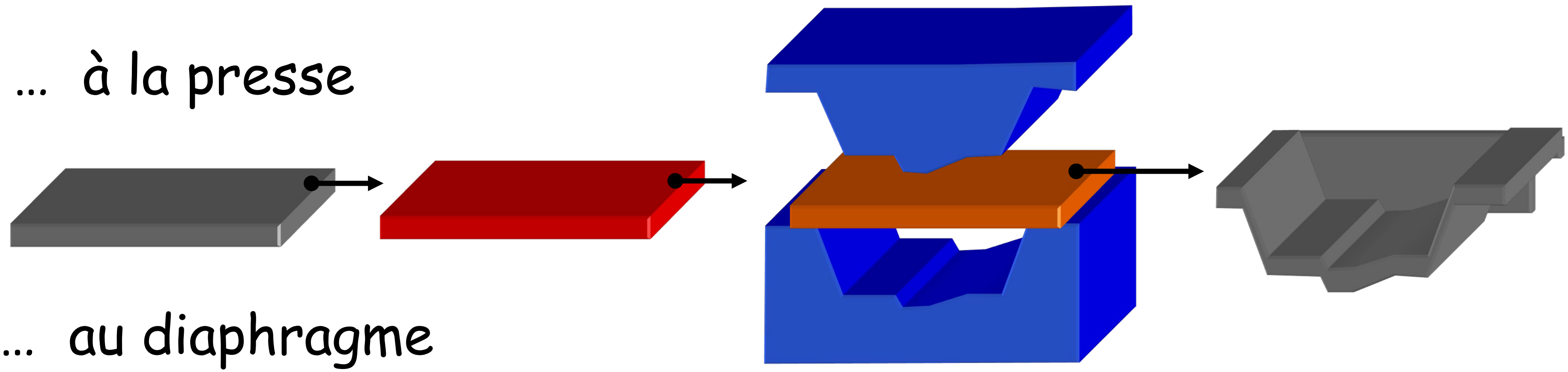
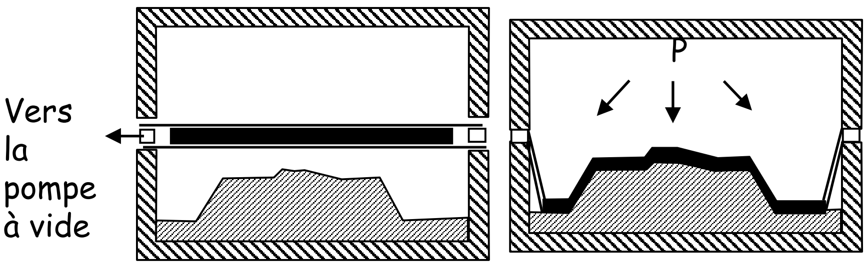
Thermoformage

... à la presse



... au diaphragme



Avantages :	**Inconvénients :**
Formes complexes Cadences élevées Bonne qualité des pièces	Investissements importants Contrôle des transferts de chaleur

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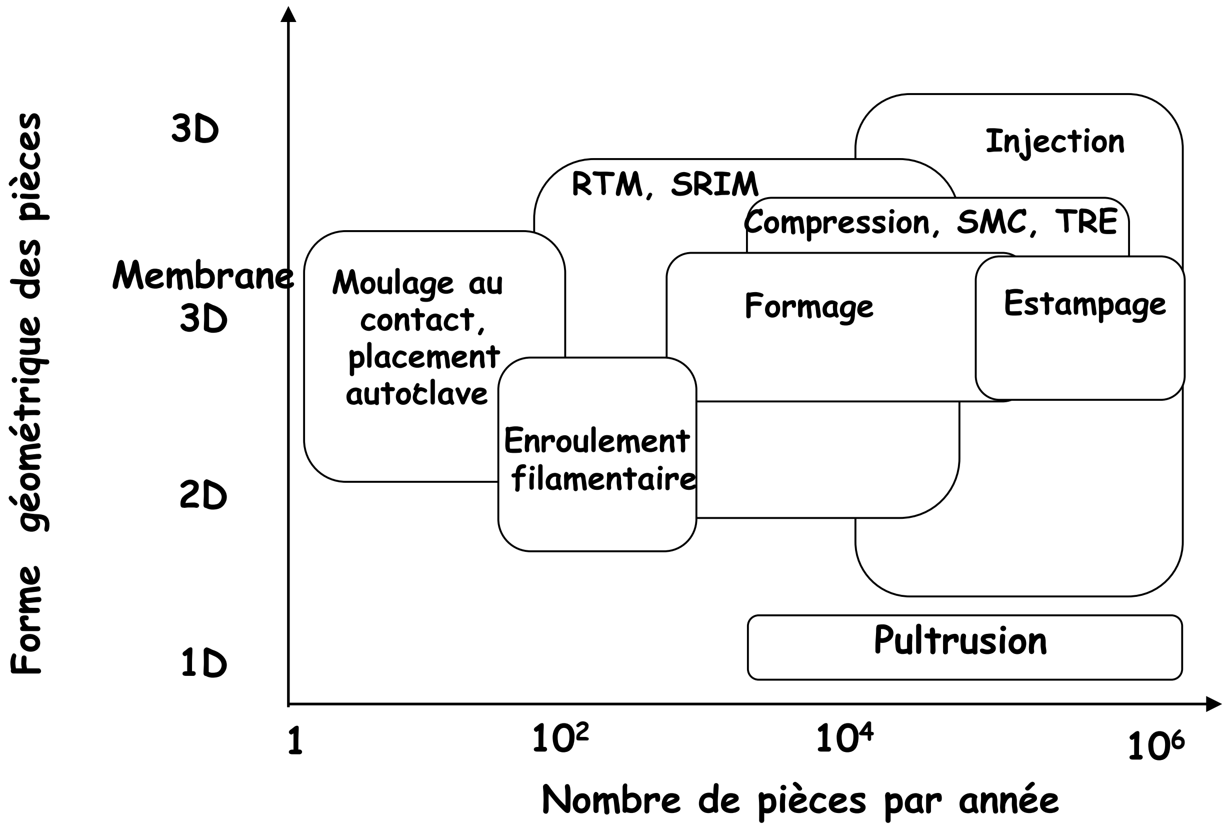
Sélection



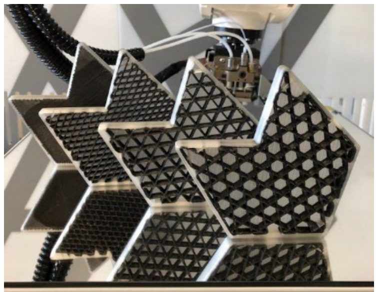
Forme géométrique des pièces
3D
Membrane 3D
2D
1D
Injection
RTM, SRIM
Compression, SMC, TRE
Moulage au contact, placement autoclave
Formage
Estampage
Enroulement filamentaire
Pultrusion
1
10^2
10^4
10^6
Nombre de pièces par année

Sélection

	Faibles volumes	Grands volumes
Types d'industries	Aérospatiale, militaire	Transport, ind. mécanique
Performances désirées	Rigidité et résistance spécifique élevées	Liberté de conception et de géométrie complexe
Coût	'peu' important	très important
Prix des matériaux	50 à 200 CHF/Kg	2 - 20 CHF/Kg
Matériaux dominants	Thermodurcissables et thermoplastiques avec des fibres continues	Thermoplastiques et thermodurcissables avec des fibres courtes
Techniques de fabrication	Dépose de préimprégnés, autoclave, RTM	Moulage par injection, moulage par compression, pultrusion

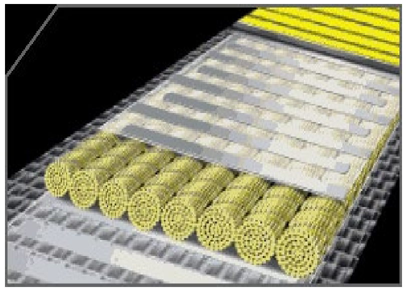
R&D&A

3D printing



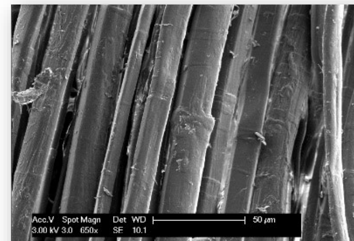
Anisoprint

Functional composites

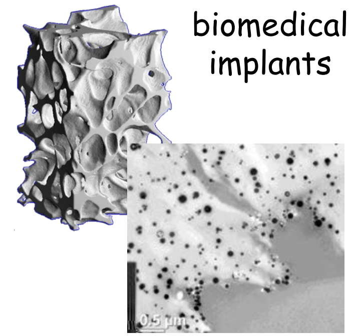


Biocomposites

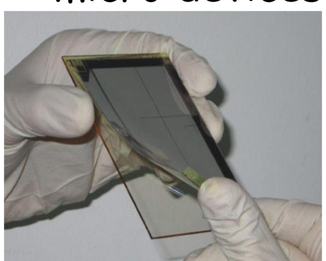
Natural fibres composites

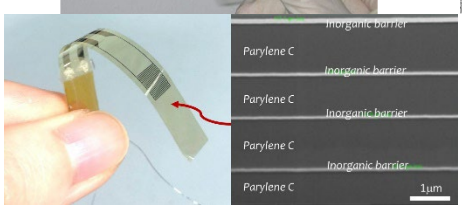


Resorbable biomedical implants

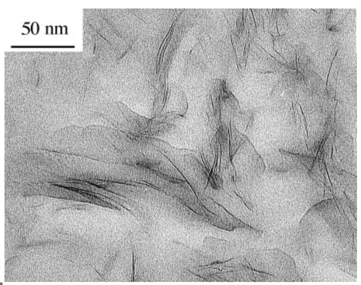


Thin films and micro devices

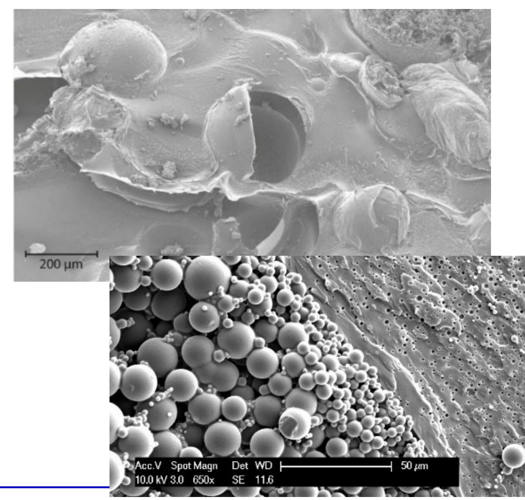




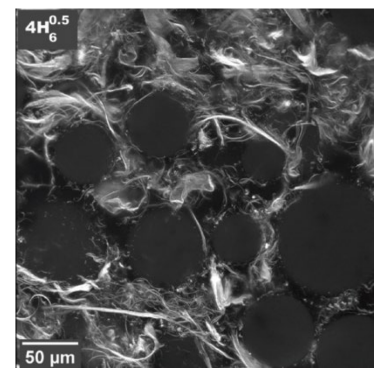
Nanocomposites



Self-healing composites



Hydrogel composites



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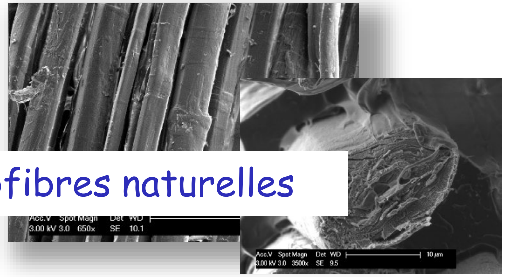
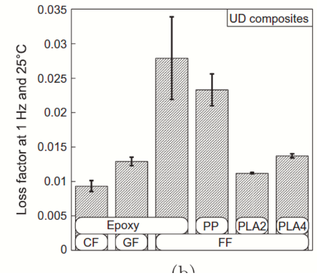
https://www.epfl.ch/labs/lpac/

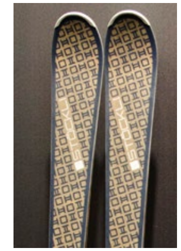
Biocomposites

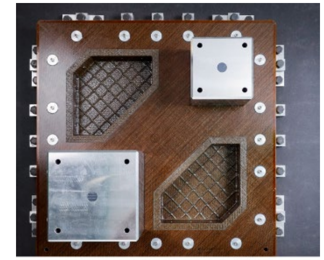
Biocomposites à fibres naturelles



Amortir avec des biofibres naturelles

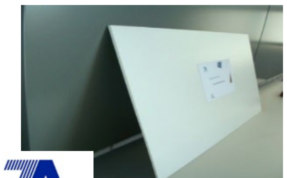






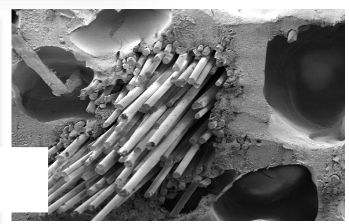
Composites biodégradables

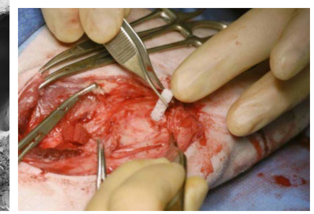
Mousses dégradables renforcées de fibres naturelles pour l'emballage

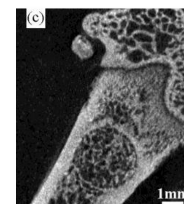


SMART-X natura

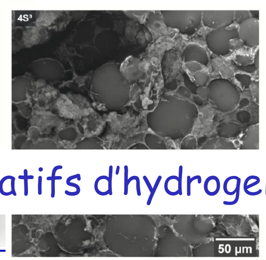
Composites polymères pour le biomédical

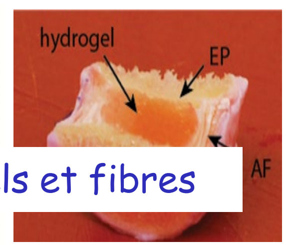


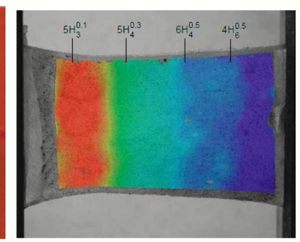




Implants résorbables de polymères et céramiques







Composites déformables et dissipatifs d'hydrogels et fibres

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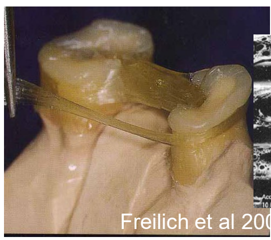
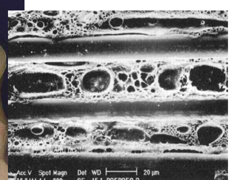
Composites for dental restoration

- **Dental filling**: Acrylate resin +33-78 wt% (quartz,baryum glass,colloidal silica)


Material	E_c (GPa)	σ_c (MPa)
Composite resin	10-16	170-260
Dentin	11.0	39.3

Challenges : wear, brittleness, shrinkage

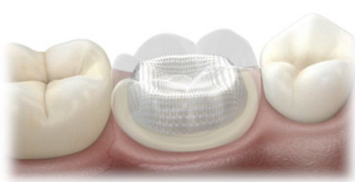
- **Dental bridge, crowns, restorations**: dental resins + glass fibers, Kevlar or UHMWPE

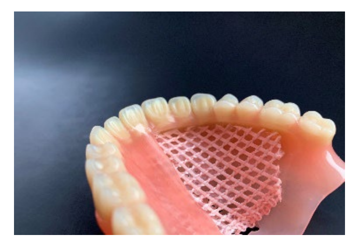



Fibers	vol%	$\sigma_{transverse}$ (MPa)
UHMWPE	48	188
glass	33	265

Challenges : impregnation, interfaces, shrinkage, conversion degree…



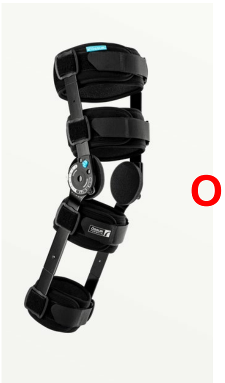




https://www.dentapreg.com

EPFL *pierre-etienne.bourban@epfl.ch*

Ortheses and prostheses



Ortheses

https://www.ossur.com https://www.ottobock.ch

Prostheses for sports

https://www.plusport.ch/fr/

https://www.sofia-g.ch/

Prostheses

Preimpregnated carbon-epoxy

(+) • lightness, tailored stiffnesses,minimum dimensions
- fiber quality, quantity and orientation : prices
- deformable parts, very elastic, strain energy
- improved reliability and comfort

(-) longer manufacturing, cost, testing device required

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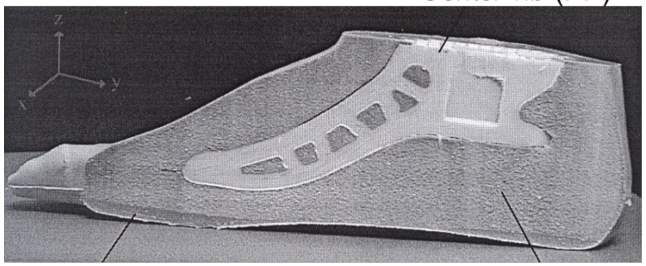
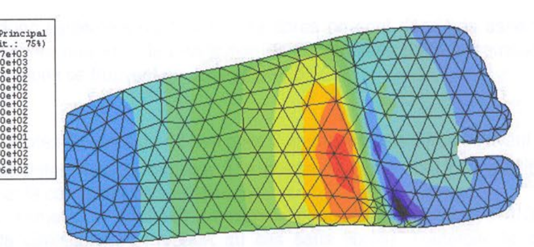
Affordable Prostheses

ICRC

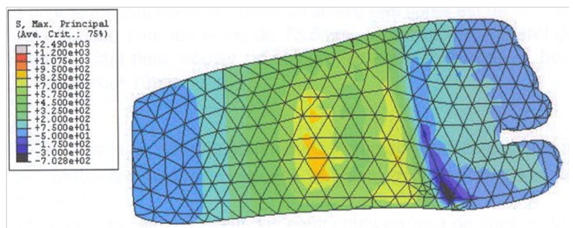
Minimal cost and maximal life time: feet for ICCR



Challenge: fatigue cracks at the top of the center rib



Without additional reinforcement σ_{max}=1.2 MPa



With UD glass fibers σ_{max}=0.85 MPa

Reduction of stress concentration by adding fibres

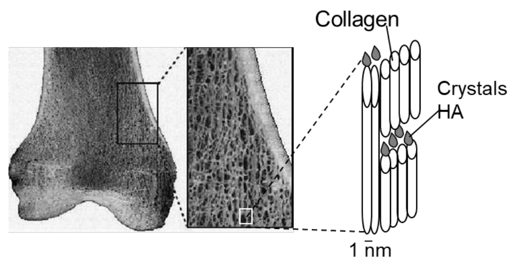
Gugolz, Rion, EPFL

Improve comfort via spring effect

https://blogs.icrc.org/inspired/2019/05/05/affordable-feet-icrc-agilis-prostheses/

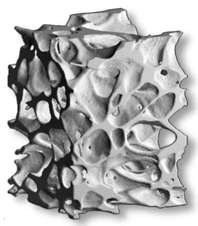
Biocomposites

Composites polymères pour le biomédical

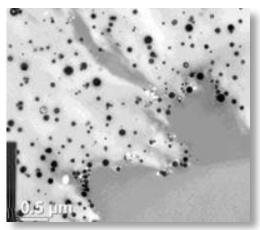


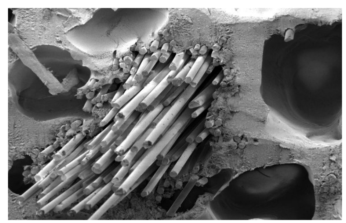
Implants résorbables de polymères et céramiques

Polymère biorésorbable

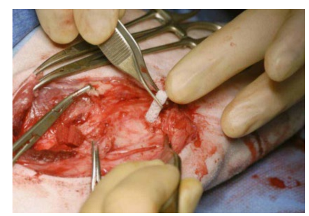


Procédé de moussage physique au CO_2 supercritique

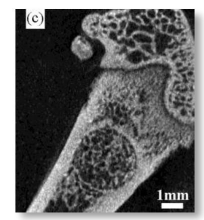




Moussage avec particules et fibres de biocéramique



Propriétés in vitro et in vivo

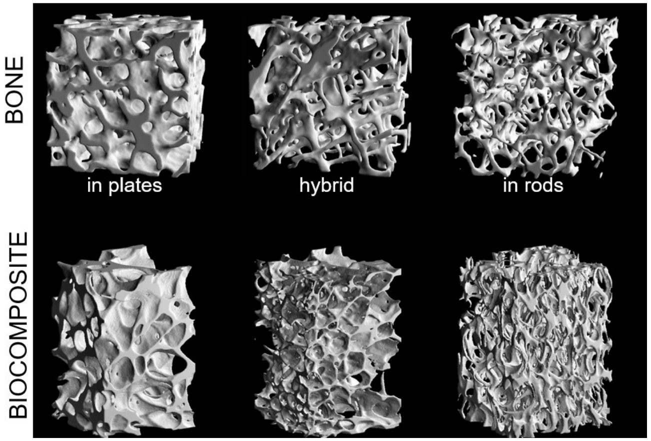


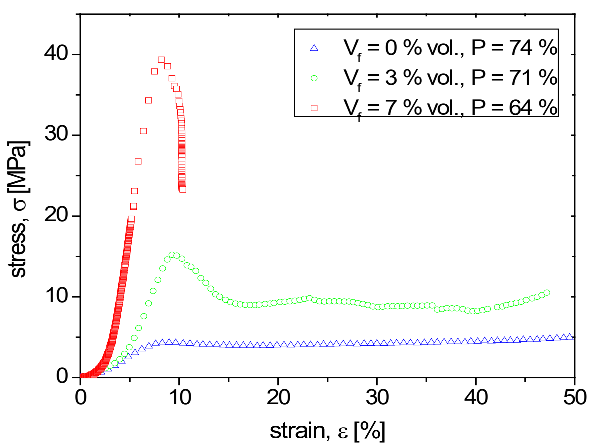
Croissance de l'os naturel

pierre-etienne.bourban@epfl.ch

Cellular composites

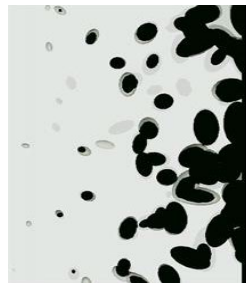
CO_2 Physical foaming of thermoplastic polymers



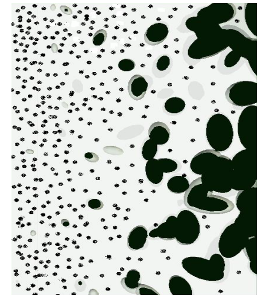


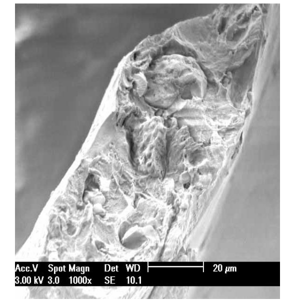
L. Mathieu

Porosity gradient



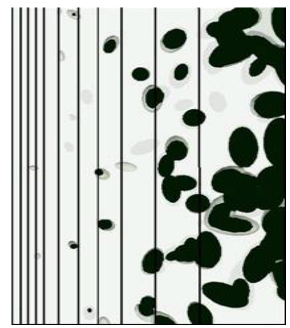
...with fillers

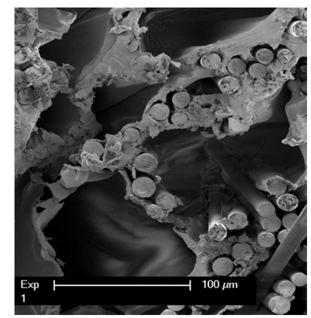




...MPa

+ gradient of long and continuous fibres





...GPa

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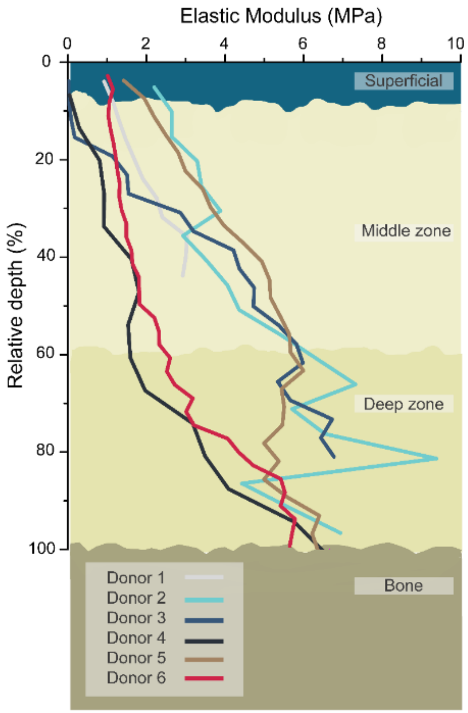
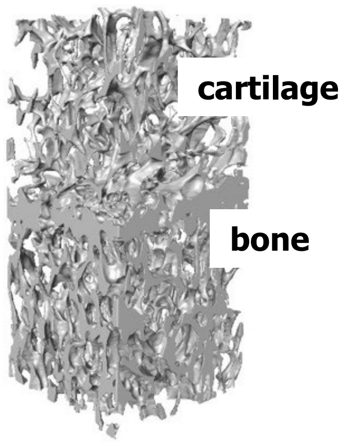
Cellular composites

Gradients of stiff and soft cellular implants



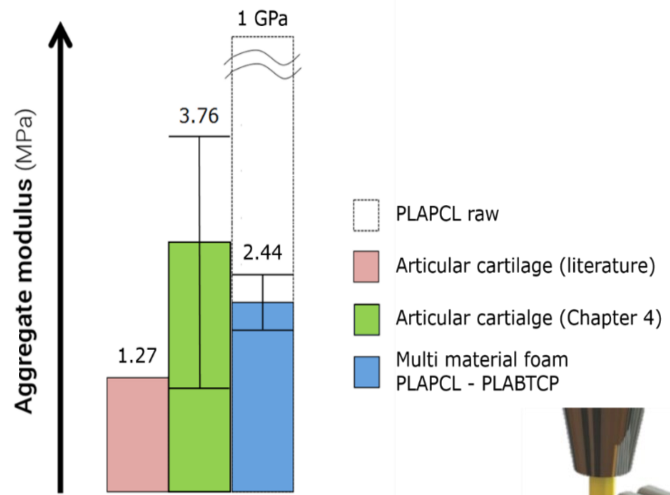
Variation of modulus in cartilages

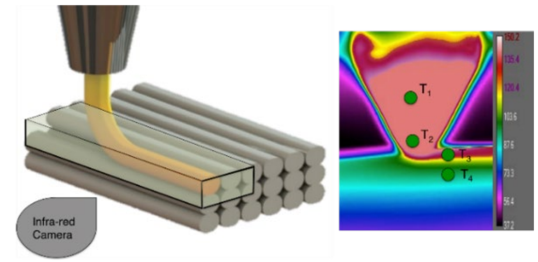
Copolymers

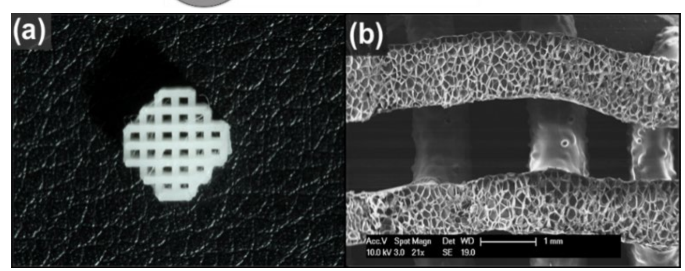


Polymer composites

M. Cuénoud







Direct 3D foam printing M. Marascio

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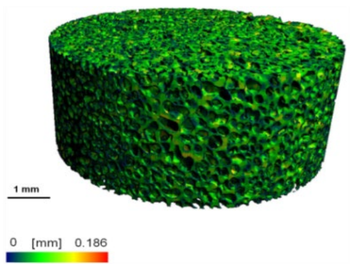
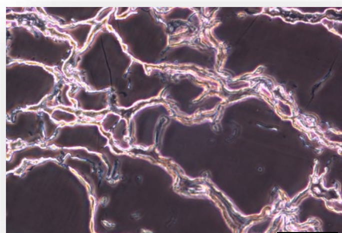
Biocomposites

Composites biodégradables





Procédé de moussage physique de biopolymères

Composites cellulaires de fibres de cellulose et bois

Emballages et structures temporaires

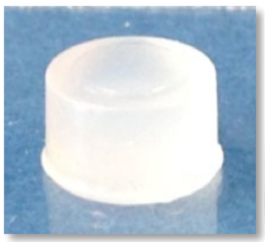
C. Boissard

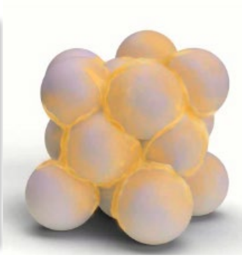
pierre-etienne.bourban@epfl.ch

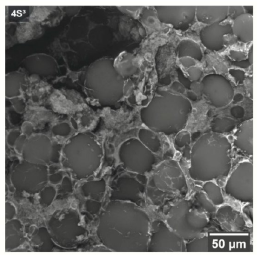
Biocomposites

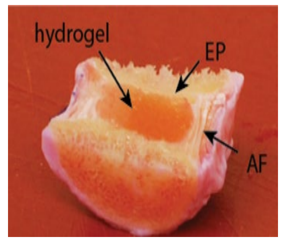
Composites polymères pour le biomédical

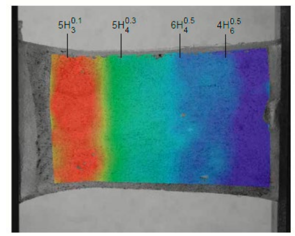
Implants déformables et dissipatifs d'hydrogels et de fibres

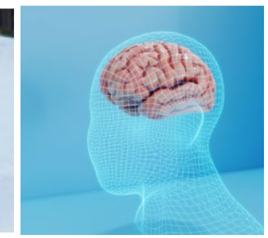












Hydrogels polymères

Auto renforcés in situ par des fibres de soie.

Propriétés dissipatives et de fatigue pour les disques intervertébraux

Gradients de déformation imitant ceux des tissus vivants

Iono-hydrogels pour atténuer les dommages au cerveau

C. Wyss et al, Soft Matter, 2021,17, 7038

C. Wyss et al, Extreme Mechanics Letters 24 (2018) 66-74

P. Karami et al, Macromol. Rapid Commun. 2021, 42, 2000660

V. Varanges et al, ACS Appl. Eng. Mater. 2024, 2, 2369-2378

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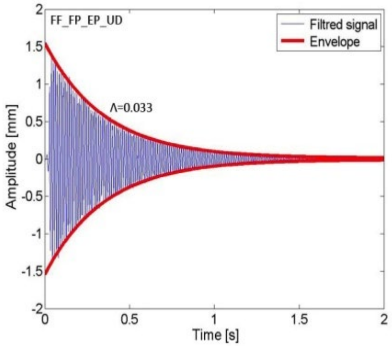
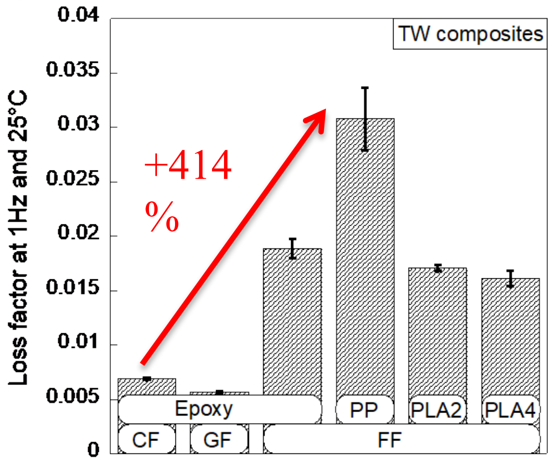
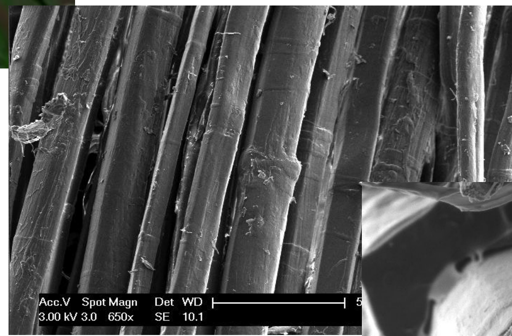
Biocomposites

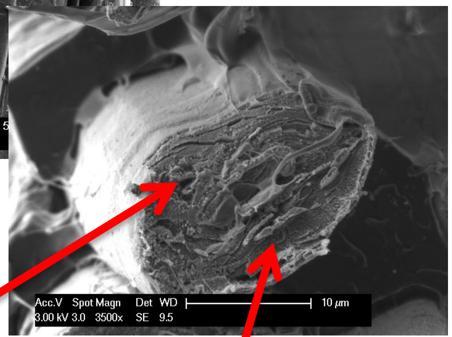
Biocomposites à fibres naturelles

Amortir avec des biofibres naturelles









Fabien Duc

Inter-cell wall friction
Friction between the cell walls

Intra-cell wall friction
Friction between cellulose and hemicellulose

Natural Fibres Composites

Thermoset NFC

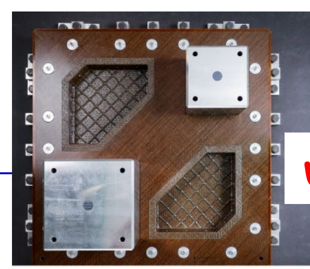
- SMC, prepreg
- UP, Epoxy, VER, Phenolic
- Jute, flax, hemp…

- Modulus E ~ 10-20 GPa
- Strength ~ 200-300 MPa
- With fibre treatment : + 15-50% E

Museeuw:
flax/carbon epoxy

Artengo: flax(5%)/
carbon epoxy

Stockli



www.Bcomp.ch

Thermoplastic NFC

- Mainly GMT
- PP, PET, PE
- Flax, wood…

- E ~ 6 GPa (PP), 20 GPa (PET)
- Strength ~ 100 MPa
- specific properties higher than GF/PP

Quadrant load floor of the Porsche Cayenne: PP reinforced with 40% kenaf, flax, wood and glass

FlexForm door panel from the Mercedes M-Class and R-class: jute(50%)/glass PP

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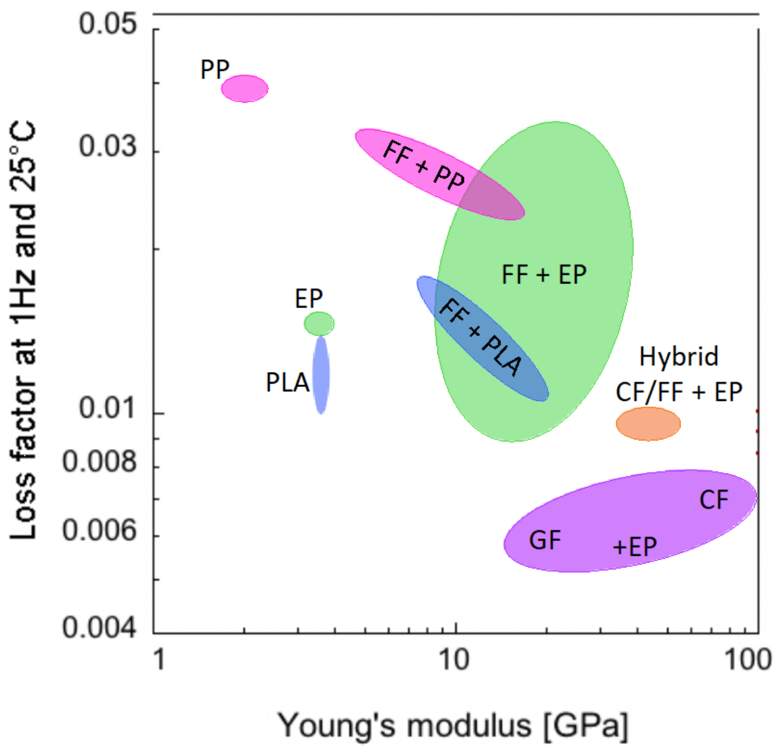
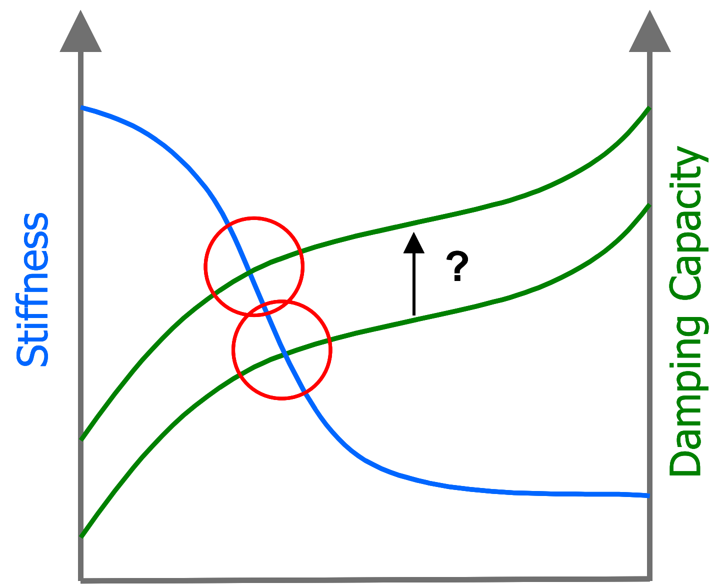
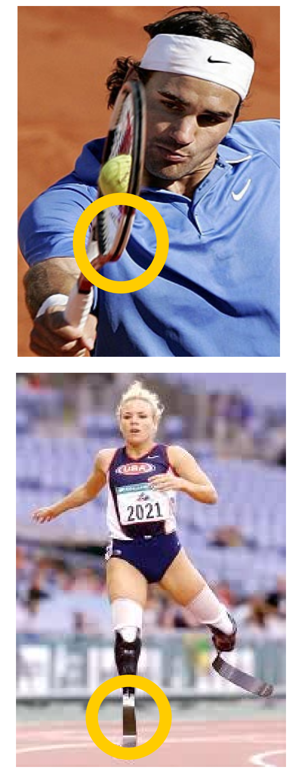
Damping and stiffness



Fabien Duc

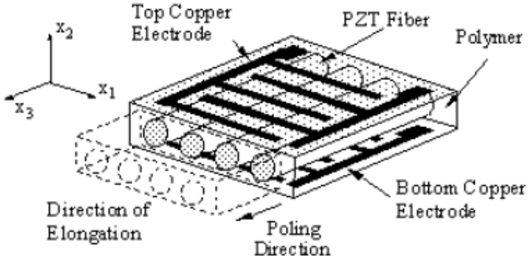
Feel and control

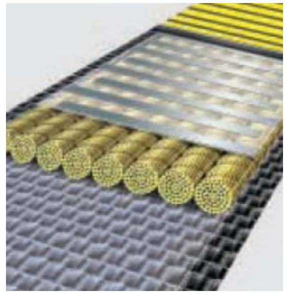




EPFL pierre-etienne.bourban@epfl.ch

Composites actifs

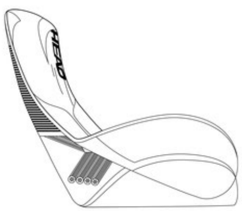


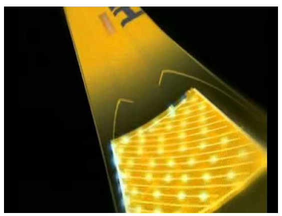


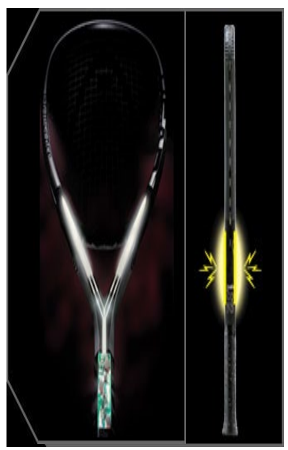
Matériaux piézoélectriques
Alliages à mémoire de forme

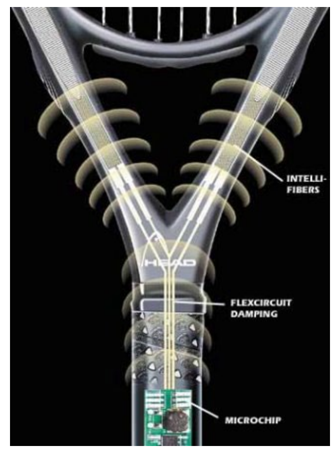
Vibrations et amortissements

Changement de formes

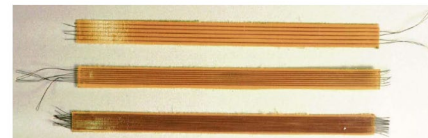


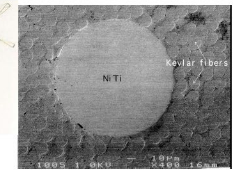


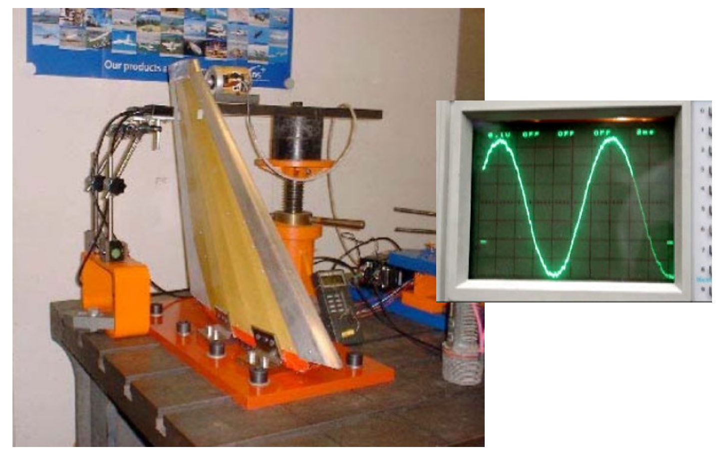




Head Intelligence Technology





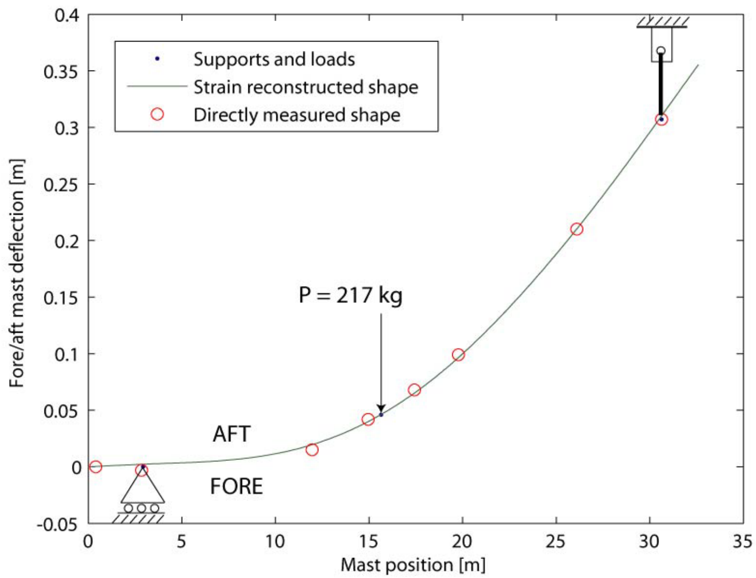


Demonstrator manufactured
in the ADAPT project

pierre-etienne.bourban@epfl.ch

Fibres optiques pour des mesures en temps réel

Déformations de matériaux, flexion de structures…

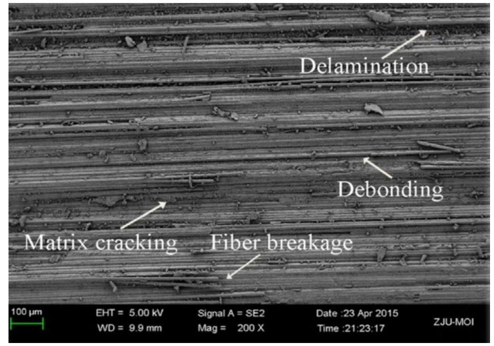


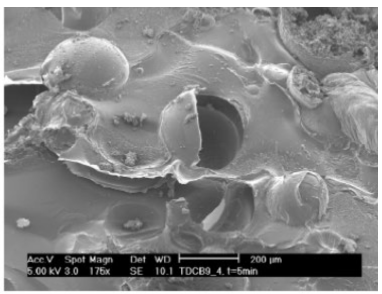
IOA-EPFL, D. Costantini
Antoine Sigg Fiber Optic

Composites auto-réparants

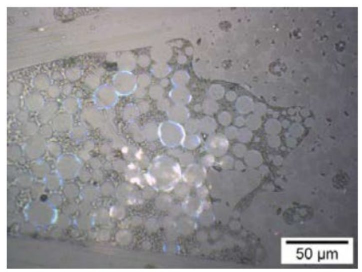
Cicatrisation, réparation des dommages engendrés lors d'impacts

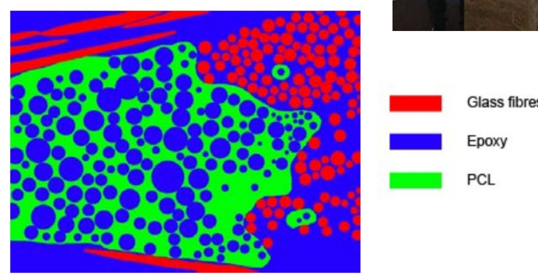
Réparation des griffures de surface





Kirkby, 2005





Cohades, 2017

Microcapsules de monomères

Mélange de polymères TD et TP

COMPPAIR

pierre-etienne.bourban@epfl.ch

Why polymer nanocomposites ?

Increased strength and stiffness: while maintaining the high elongation of the matrix.
Permeation Resistance: (plate-like fillers e.g. exfoliated clays) interest in nanocomposites barriers from packaging companies.
Transparency: low loadings and filler dispersion maintain inherent polymer transparency in thin sections (again interest for packaging)
Recyclability: nanofillers are not affected or degraded during processing → physical properties not seriously affected by recycling
Flame resistance: rapid char layer formation, excellent flame resistance
Transport properties: percolation at very low loadings in high aspect ratio systems, important for thermal, electrical conductivity (e.g. carbon nanotubes)
Functionality: bioactivity, hydrophilicity, magnetic and electrical properties etc. etc.

And all at loadings of a few wt% ***weight saving!!***

Are nanofillers worth it? Examples (2019)

- Natural clays (mined, refined, and treated)—\$3–\$15/lb.
- Synthetic clays—\$10–\$20/lb.
- Nanostructured silicas—\$5–\$200/lb.
- Nanoceramics—\$100–\$280/lb.
- Nanotubes (carbon based, MWNT)—\$100–\$200/lb.

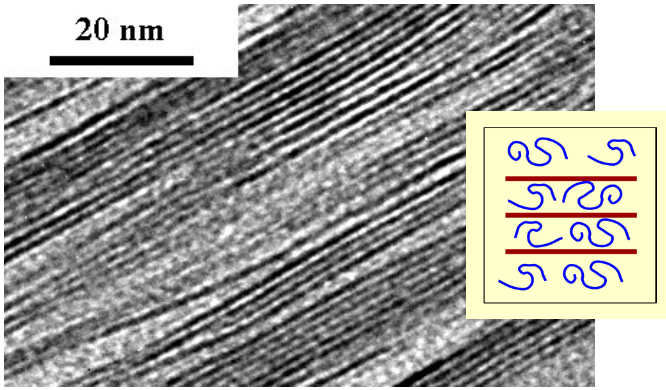
Applications now include packaging, automotive, and wire and cable industries, and huge increase in demand for these fillers is projected
→ Lower prices in the future

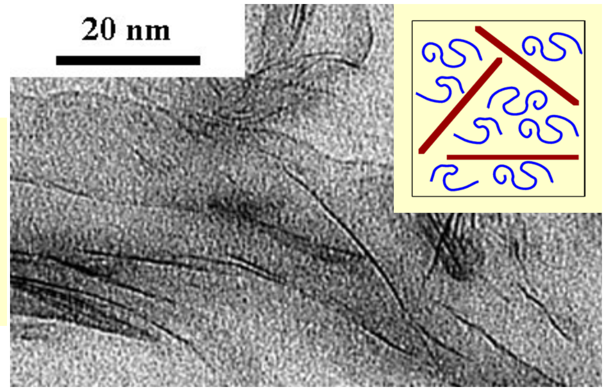
Nanocomposites

Clay-based thermoplastic nanocomposites

Without HBP

Non-exfoliated Silicate layers

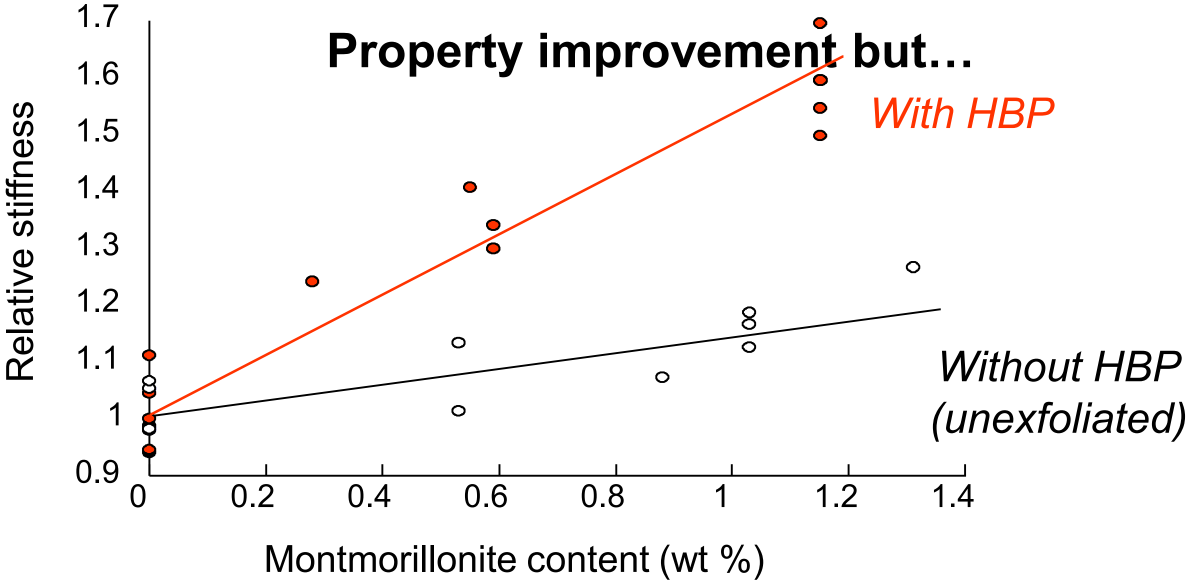




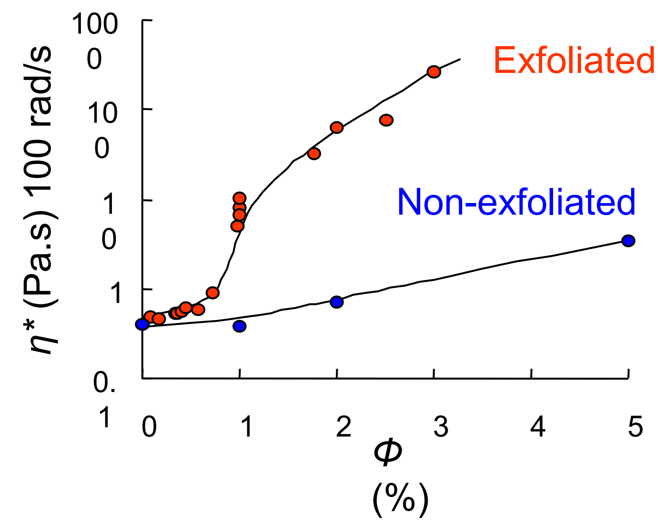
With Hyper Branched Polymer HBP

Exfoliated

Property improvement but…



…difficult to process!

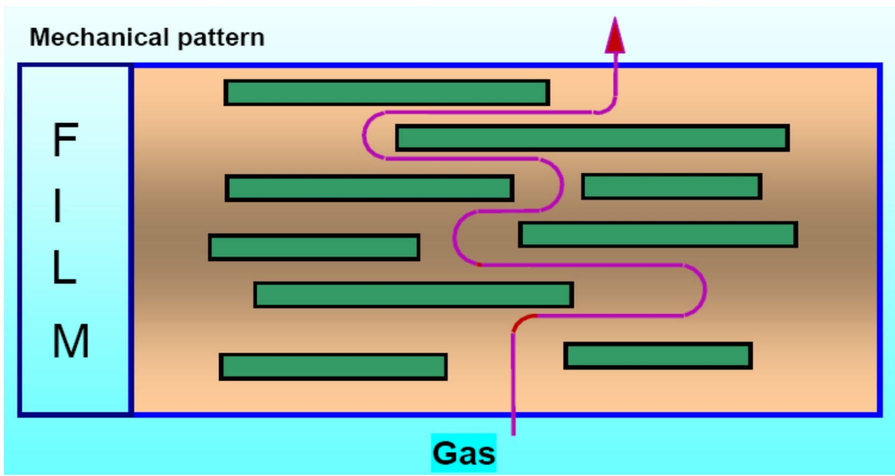


Nanocomposites

Flame retardant properties

Barrier property improvements

Improvement of barrier properties with montmorillonite layers oriented perpendicular to the diffusion path: "tortuosity effect"

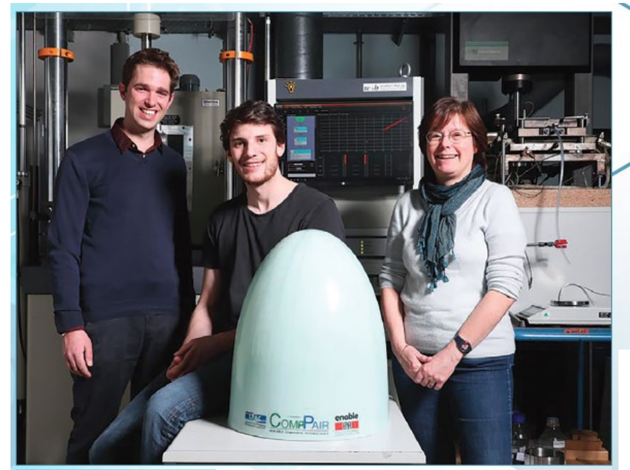


Electrical conductivity with carbon nanotubes or graphene

à… de… avec… l'EPFL

https://www.startup.ch/flyability

turtle shell



Self-repair part developed at LPAC (JCM issue 128, May-June 2019)

CompPair
HEALABLE COMPOSITE TECHNOLOGIES

http://www.comppair.ch


Hublot watches

Consumer electronics

Bcomp's powerRibs™ technology is also entering consumer electronic sector. With the outstanding stiffness-to-weight ratio combined to the high damage tolerance and low carbon footprint, powerRibs™ composite material is a novel solution for industrial designers and architects for reaching the best performance in a sustainable way. We are constantly working with the leading consumer electronic brands to come up with fully bio-based thermoplastic solutions in order to influence the market and make our world a better place to live.

Bcomp®

http://www.bcomp.ch/

pierre-etienne.bourban@epfl.ch

Observe and race

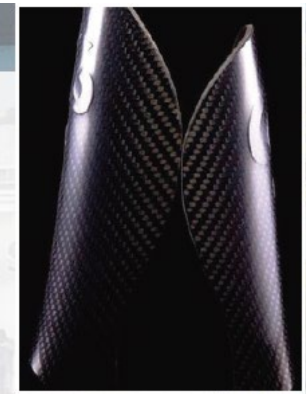
The Bolt disrupts the drone racing market with an easy-to-use and affordable carbon-fibre frame drone (US$200 starting pack). This drone makes First Person View (FPV) piloting and racing available to everyone, as it offers three different control mods: Line of Sight, Screen on Controller, and First Person View (FPV) goggles. That means that drone racing is not left just to the pros, but is accessible to audiences of all skill levels. The Bolt Drone is the only complete set on the market that includes the carbon-fibre drone, an HD screen, FPV goggles, controller, and more.

www.boltdrones.com

Protect your body

The C6 weighs only half as much as other current shin guards (34 g vs. 74 g). The fourth generation of these shin guards feature a 100% aerospace-grade prepreg carbon fibre/epoxy shell. The increased carbon content for Gen 4 further improves its strength and shock resistance. The shin guards come with a lifetime guarantee and have been reviewed by the specialized soccer community and sports magazines as being the best ones on the market.

www.c6agility.com



More lightweight for off-road uses

The new HD Sport Edition Camera from Xcel is a user-friendly tactical action recording device, ideal for active outdoor enthusiasts and perfect for mounting on a car, boat, ATV or a helmet. Designed by the same company as SpyPoint range cameras, the Xcel HD camera captures beautifully sharp, full high-definition 1080p videos with sound and takes stunning 5 Megapixel high-resolution images. In the air, on land, or under water, the HD Sport Edition camera from Xcel allows you to replay, enjoy and share every moment of your action-packed day in virtually all weather conditions. Thanks to its carbon-fibre camera body, the Xcel Sport Edition weighs in at only 85 grams.

www.spypoint.com

Sturdy and shockproof

UAG iPhone Xs Max (6.5-inch) cases are ready to protect your iPhone from all drops, shock, and impact. The Pathfinder Series case encompasses a premium design and precise engineering to provide a case that meets double the Military Standard for drop & shock protection. Urban Armor Gear iPhone 10 MAX cases are an example of high-level engineering, boasting military-grade drop & shock protection for your iPhone. These also meet double the Military drop-test standards (MIL STD 810G 516.6). The Pathfinder Series Cases feature composite construction with an armour shell and impact-resistant soft core. Each case is equipped with scratch-resistant skid pads and screen surround for maximum device protection.

https://urbanarmorgear.com